The response of plastic scintillator to protons and deuterons

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Abstract
Data on the absolute light output \( L(E) \) of plastic scintillator, in equivalent electron energy, to protons with energies up to 20 MeV have been fitted with the parameterization

\[
L(E) = A \int_0^E \ln \left[ 1 + \alpha \left( \frac{dE}{dx} \right) \right] \, dx,
\]

where \( E \) is the initial particle energy, \( dE/dx \) is the specific energy loss, \( R \) is the particle range, and \( \alpha \) is the only free parameter. The scaling factor \( A \) has been expressed in terms of \( \alpha \) and the specific energy loss for a minimum ionizing particle, producing an absolute response curve. The best-fit value was determined to be \( \alpha = (0.025 \pm 0.002) \) g cm\(^{-1}\) MeV\(^{-1}\), which gives a normalization of \( A = 41.0 \) MeV/(g/cm\(^2\)). The results of the parameterization were compared with absolute response data for protons up to 150 MeV, and deuterons up to 120 MeV, with excellent agreement being observed.

1. Introduction

Many organic compounds scintillate when exposed to nuclear radiations, with the light being emitted in response to the ionization produced by the incident radiation. This ionization may be produced directly by a charged particle or, for neutral radiation such as \( \gamma \)-rays and neutrons, by recoil electrons or recoil nuclei resulting from interactions within the scintillator material.

As a charged particle travels through the scintillator material it will lose energy by producing a column of ionized and excited molecules along and near its path. When these excited molecular states decay, a small fraction of the ionization energy lost by the particle is emitted as light via fluorescence de-excitations. The remainder of the energy is dissipated non-radiatively, mainly in the form of lattice vibrations or heat [1]. The fraction of energy emitted as fluorescence light is referred to as the scintillation efficiency.

Ideally, the scintillation efficiency would be independent of the incident particle energy, leading to the light output being proportional to the energy deposited in the scintillator. This is often true for inorganic scintillators such as NaI, however, for organic scintillators, the scintillation efficiency is found to depend on the particle type and energy. As a result, organic scintillators display nonlinear energy responses, particularly for low-energy particles [1].

2. Observed response of organic scintillators

The response of organic scintillators to electrons is known to be a linear function of the deposited energy for electron energies above approximately 100 keV. Furthermore, extrapolation of this linear response passes within a few keV of the origin [1,2]. Thus, for electrons, the light output is related to the deposited energy via

\[
L_e = g E_e - c.
\]

\( L_e \) is the light output for an electron depositing energy \( E_e \) in the scintillator, \( g \) is a scaling factor (scintillation efficiency \( \times \) normalization), and \( c \) is an offset (which is negligible).

For more heavily ionizing particles, such as protons and deuterons, the response of an organic scintillator is observed to be a nonlinear function of the deposited energy to much higher energies. Also, the light output is always less than that produced by an electron of the same energy. The measured absolute response of NE-102 plastic scintillator to stopped electrons and protons, with energies below 4 MeV, is shown in Fig. 1.
3. Theoretical description of the response

There are various theoretical explanations for the non-linear response observed for heavy particles in organic scintillators [1,3,4]. These are based on the assumption that a high ionization density along the particle track results in quenching of the primary fluorescence process, with a consequent reduction in the scintillation efficiency. The details of this ionization quenching are not well understood.

Birks [1] has proposed a unimolecular process for this quenching mechanism. In this model the molecules along the ionization column produced by the charged particle are considered to be either damaged or undamaged, with the damaged molecules being responsible for dissipating the ionization energy nonradiatively (quenching). The density of damaged molecules is assumed to be proportional to the ionization energy loss, $B(\Delta E)$, with some fraction $k$ of these damaged molecules leading to quenching. Birks makes the additional assumption that, in the absence of quenching, the light output is proportional to the energy loss, and obtains the following expression for the differential light output;

$$\frac{dL}{dx} = S \frac{dE}{dx} \left[ 1 + kB \left( \frac{dE}{dx} \right) \right]^{-1}. \tag{2}$$

$\frac{dL}{dx}$ is the light output per unit path length, $S$ is the absolute scintillation efficiency, and $B$ is a constant relating the density of damaged molecules to $dE/dx$. The product $kB$ is treated as a single parameter which is adjusted to fit the experimental data for a particular scintillator.

Chou [4] has proposed an empirical extension to Birks’ relationship to better fit the observed light output for scintillators at lower energies;

$$\frac{dL}{dx} = S \frac{dE}{dx} \left[ 1 + kB \left( \frac{dE}{dx} \right) + C \left( \frac{dE}{dx} \right)^2 \right]^{-1}. \tag{3}$$

As with the term $kB$, $C$ is treated as an adjustable parameter when fitting to the data.

Wright [3] has suggested a different quenching mechanism consisting of both unimolecular and bimolecular processes, with the latter being important for heavily ionizing particles. In this model the energy $E$ remaining in a segment of the ionization column at time $t$ is dissipated by either the fluorescence mechanism, at a rate $pe$, or the quenching processes, with rates of $ke$ and $ae^2$ for the unimolecular and bimolecular processes respectively, giving a total rate of energy dissipation

$$\frac{de}{dt} = -(p + k + ae)e. \tag{4}$$

The fluorescence light output $dL$ from this path segment is given by

$$\frac{dL}{dx} = \int_0^\infty pe \, dt = p \int_0^\infty \left[ \frac{-1}{(p + k + ae)} \right] \, de. \tag{5}$$

This gives the following expression for the light output;

$$\frac{dL}{dx} = A \ln \left[ 1 + \alpha \left( \frac{dE}{dx} \right) \right], \tag{5}$$

where $A$ is a scaling parameter ($A = p/a$), related to the absolute scintillation efficiency, and $\alpha$ is a quenching parameter ($\alpha = a/(p + k)$). It should be noted that for small values of $dE/dx$ both Chou’s relation (Eq. (3)) and Wright’s (Eq. (5)) for the differential light output reduce to Birks’ original expression (Eq. (2)). Radhwar [9] has shown that Birks’ expression describes the light output for values of $dE/dx$ less than about $100 \text{MeV/g/cm}^2$. At higher ionization densities the light output deviates from the predictions of Birks’ expression and is better described by that of Chou or Wright.

4. Calculation of light output

For this work the parameterization of Wright was used to calculate the light output for a charged particle traversing a plastic scintillator. For a particle of energy $E$, the total light output is determined by integrating Eq. (5) over the range $R$ of the particle;

$$L(E) = A \int_0^R \ln \left[ 1 + \alpha \left( \frac{dE}{dx} \right) \right] \, dx. \tag{6}$$
The calculation of \( L(E) \) was performed by numerical integration techniques. The specific energy loss for different particle types in the scintillator material was calculated using the Bethe–Bloch formula, with appropriate shell-corrections at low energies, down to 10 keV particle energy. Below this energy the specific energy loss was taken to be constant down to zero particle energy; this will introduce a very small systematic uncertainty to the light output curve \( L(E) \) which can be neglected in the present work.

The specific energy loss calculated for proton with energies between 50 keV and 1000 MeV were compared with the tabulated energy loss values of Janni [10]; the two values agreed to within 2%, which is comparable to the anticipated error in the calculations.

No attempt has been made to evaluate the absolute scintillation efficiency or the related quantity \( \alpha \), since this is dependent upon the storage history of the particular scintillator and its exposure to light and other radiations. Instead, the light response was normalized to express \( L(E) \) in terms of the electron energy which would produce the same light output, this is referred to as the equivalent electron energy.

For electrons and other minimum ionizing particles, the specific energy loss \( (dE/dx)_{\text{min}} \) is constant along their path. The light output is known to be a linear function of the deposited energy \( (E_{\text{dep}}) \), and the scintillator-photomultiplier tube (PMT) gain for a detector is defined as

\[
\text{gain} = \frac{L(E)}{E_{\text{min}}} \tag{7}
\]

where gain includes the fraction of generated light which reaches the PMT, the PMT quantum efficiency and amplification, the ADC conversion gain, and the relation between ADC value and energy.

Since the energy loss is constant, the light output is given by

\[
I(E) = A \ln \left[ 1 + \alpha \left( \frac{dE}{dx} \right)_{\text{min}} \right] \Delta x \tag{8}
\]

where \( \Delta x \) is the path length through the scintillator. The energy deposited in the scintillator by a minimum ionizing particle can be expressed as

\[
E_{\text{min}} = \left( \frac{dE}{dx} \right)_{\text{min}} \Delta x \tag{9}
\]

Substituting the above two expressions (8) and (9)) into Eq. (7) produces the following expression for the scintillator-PMT gain:

\[
\text{gain} = \frac{A \ln \left[ 1 + \alpha \left( \frac{dE}{dx} \right)_{\text{min}} \right]}{\left( \frac{dE}{dx} \right)_{\text{min}}} \tag{10}
\]

Now, consider a different particle \( p \) which stops in the scintillator. The light output for this particle is given by

\[
L_p(E) = A \int_0^R \ln \left[ 1 + \alpha \left( \frac{dE}{dx} \right)_{\text{min}} \right] \frac{dE}{dx} \, dx \tag{11}
\]

where \( R \) is the particle’s range. Using expressions (7), (10), and (11), \( L_p(E) \) can be expressed in terms of the equivalent electron energy \( (E_{\text{eq}} = E_{\text{min}}) \) deposited in the scintillator:

\[
E_{\text{eq}} = \frac{\int_0^R \ln \left[ 1 + \alpha \left( \frac{dE}{dx} \right)_{\text{min}} \right] \frac{dE}{dx} \, dx}{\ln \left[ 1 + \alpha \left( \frac{dE}{dx} \right)_{\text{min}} \right]} \tag{12}
\]

The normalization is relatively insensitive to the value of \( (dE/dx)_{\text{min}} \), an uncertainty of 5% in the value of the minimum energy loss introduces a variation of less than 0.1% in the normalization.

The absolute response data for protons below 20 MeV stopping in NE-102 plastic scintillator were fitted using Wright’s parameterization (Eq. (6)), with the normalization given by Eq. (13). An initial value \( \alpha = 0.023 \, \text{g cm}^{-2} \, \text{MeV}^{-1} \) (as suggested by Gooding and Pugh [11]) was chosen. The value of \( \alpha \) was adjusted to minimize \( \chi^2 \). The best fit value of \( \alpha \) was determined to be \( \alpha = (0.025 \pm 0.002) \, \text{g cm}^{-2} \, \text{MeV}^{-1} \) which gave a reduced \( \chi^2 \) of 1.4 when fit to the absolute response data between 1 and 20 MeV. The normalization (Eq. (13)) is then 41.0 MeV/(g cm\(^{-1}\)).

The absolute response data for protons below 20 MeV stopping in NE-102 plastic scintillator are displayed in Fig. 2. The solid curve is the light response calculated using Wright’s parameterization with the best-fit value determined above. The dot dashed curve is the results of the Chou parameterization using the fit determined by Craun and Smith \( (kB = 0.0129 \, \text{g cm}^{-2} \, \text{MeV}^{-1}) \) and \( C = 9.59 \times \)
The absolute response data for protons and deuterons have been determined from a measurement of $^3$He($\gamma,p$) [13] using the Saskatchewan–Alberta Large Acceptance Detector (SALAD) [14] and the photon tagging system at SAL [15]. Both the proton and deuteron were detected, and the photon energy was known from the photon tagger, kinematically over-determining the reaction. This allowed the kinetic energy of each particle to be calculated using the tagged photon energy and the measured particle track angle. The absolute gains of the SALAD calorimeter were determined using cosmic rays and, with these, the energy deposited by each particle in terms of the equivalent electron energy ($E_{e}$) was determined. This provided absolute response data for protons from 80 to 150 MeV, and deuterons from 12 to 68 MeV [16].

The relative response of the NE-102 plastic scintillator for protons with energies from 24 to 146 MeV, and deuterons with energies from 41 to 119 MeV has been measured by Gooding and Pugh [11]. The measurements of Gooding and Pugh were made with an absorber placed before the full-energy detector in order to produce a more linear response curve. For this work it was necessary to correct for the energy loss in this absorber to determine the energy deposited in the scintillator. Gooding and Pugh note that this absorber was a thin piece of NE-102, and, including windows, the total thickness of material was sufficient to stop 13 MeV protons, implying an equivalent thickness of 1.92 mm NE-102. The recorded light output was normalized by taking the measured response (in arbitrary units) for the proton point at 23.8 MeV and scaling this to the value given by Wright’s parameterization. Using the scaling factor determined in this manner, the proton and deuteron response data were adjusted. Thus, the proton data provides information only about the shape of the light response curve, while the deuteron data gives information about both the shape and the relative scale.

Fig. 3 shows the response data for protons and deuterons. The solid and long dashed curves are the fit to Wright’s parameterization for protons and deuterons, respectively. The short dashed curve represents the linear response. Figs. 4 and 5 show the difference between the fit
Fig. 5. Response of plastic scintillator in equivalent electron energy (MeV$_e$) to deuterons below 120 MeV. The data are displayed as the difference with the fit to Wright’s expression. The dot dashed line is Chou’s expression with Craun and Smith’s fit.

5. Conclusion

The parameterization of Wright describing the light output of plastic scintillator to charged particles has been reduced to a one-parameter formula. This has been fit to existing proton response data up to 20 MeV to obtain a best-fit value for the parameter $\alpha$ of $(0.025 \pm 0.002) \, \text{g cm}^{-2} \text{MeV}^{-1}$. This parameterization gives good agreement with the response data for protons and deuterons up to 150 MeV. The parameterization of Chou as fit by Craun and Smith is significantly poorer in comparison with the data due to inaccurate $dE/dx$ calculations. Excellent agreement is found with a refit of Chou’s expression.

References